USE OF THE McILROY ELECTRIC ANALYZER FOR PIPELINE NETWORK ANALYSIS

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IT IS indeed a pleasure to be here this evening and present to you my experiences in the use of the direct-reading electric analyzer for the solution of complex pipeline network analyses. Although my experiences have been somewhat limited they will, I believe, acquaint you with the McIlroy analyzer and its potential value to the water supply engineer.

Those of you in the water supply field have made, or are at least aware of, the lengthy computations which are required to determine the division of flow, the loss of head, and the resulting water pressures throughout a complex water distribution system. These computations are laborious and time consuming, even though several shortcuts and improvements in the methods of computations have been devised to somewhat reduce the time required.

In 1946 Malcolm S. McIlroy conducted research and studies of pipeline network analysis and established basic design for a direct-reading electric analyzer which determines the division of flow and the loss in head in a pipeline network based on the analogous behavior of electric current in an electrical circuit and the flow of water in a pipeline. This research and studies were conducted for his doctorate at the Massachusetts Institute of Technology, where he became associated with many men eminent in the field of hydraulic and electrical engineering including several who had already devoted much time and thought to the analogies of electric current flow and the flow of water in pipeline networks and to the construction of a working analyzer.

Subsequently, as Professor of Electrical Engineering at Cornell University and as special consultant to the Standard Electric Time Co. of Springfield, Mass., Mr. McIlroy successfully constructed a test model of a direct-reading electric analyzer. This analyzer is presently located at Cornell University and has been used in the analyses of many

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gas and water distribution networks by both municipal, industrial and consulting engineers. The death of Mr. McIlroy in 1956 cut short his work at a time when his analyzer was rapidly gaining recognition and acceptance throughout the country.

Description of Analyzer

The direct-reading electric analyzer is based on the electrical analogy method of pipeline network analysis and eliminates all calculations beyond those necessary for the compilation of the basic data concerning the pipeline network and the conversion of this data to electrical equivalents. The electrical-analogy method of pipeline network analysis is based on five basic analogies as follows:

1. That the flow of current in an electric circuit is similar to the flow of water in a pipeline. The quantity of current is measured by placing an ammeter in series with the conductor just as the quantity of water is measured by placing a flowmeter in the pipeline.

2. That the drop in voltage in an electrical circuit is similar to friction head loss in a pipeline. When electrical current passes through a conductor or resistor a drop in the voltage occurs. This drop in voltage is measured by connecting a voltmeter across the extremities of the conductor or the terminals of the resistor. In a water pipeline the loss of head along the line is measured by connecting a differential pressure gage to the ends of the pipeline.

3. That the law of balanced flow at the junction of a pipeline network is analogous to the flow of electric current at a junction of an electrical circuit. That is, the flow into a junction or intersection equals the flow out of that junction or intersection.

4. That the sum of the voltage drops in a clockwise direction in any loop of an electric circuit equals the sum of the voltage drops in a counter-clockwise direction around that loop, just as the sum of the clockwise head losses equals the sum of the counter-clockwise head losses in any loop of a pipeline network.

5. The fifth and very important analogy for the use of the direct-reading analyzer concerns the voltage drop across any resistor. Whereas the current and the voltage drop across any resistor are analogous to the rate of flow and the head loss in a pipeline, they are not necessarily proportional. In the case of water flow the head loss varies nearly as the square of the flow. In electric current flow according to Ohm's law the drop in voltage is proportional to the flow and the resistance; however,

the resistance is a constant. Special non-linear resistors also called flu-istors were developed for use in the analyzer in which the voltage varies nearly as the square of the current and satisfies this basic analogy.

The direct-reading electric analyzer consists of a sheet steel panel on which is attached a number of permanently wired, four sided electrical circuits with sockets for inserting non-linear resistors on each of the four sides. This panel is usually mounted in an upright position with access to both sides. The non-linear resistors represent the pipelines and by inserting short-circuiting plugs or by leaving sockets empty or by using electrical jumpers between intersection of these sides the electrical circuits can be arranged to conform to the pattern of the pipeline network under study. The non-linear resistors which represent the pipelines resemble ordinary showcase bulbs having tungsten filaments supported on heavy nickel leads. The filament and leads are designed so that voltage varies to the 1.85 power of the current through them to correspond with the exponent of flow in a pipeline as determined by the Hazen and Williams formula. Such a condition is possible because of the variable diameters of tungsten available and the stability, long life and peculiar resistance property of this metal. The voltage along a tungsten filament varies nearly as the 1.63 power of the current through it, if the filament is protected from the atmosphere and from the cooling effects of adjacent material. Therefore, by placing the filament in a vacuum and designing the leads to result in some cooling effect, the desired exponential value of 1.85 of the current flow is obtained for the voltage drop across the non-linear resistor.

It was the development of this non-linear resistor that eliminated the trial and error runs of previously constructed electrical analyzers using linear resistors.

The withdrawals from a pipeline network are represented on the analyzer by load currents which are independent of the voltage available at the load circuit terminals. The load currents are constant current ballast lamps which operate over a fairly wide range of voltage, and an adjustable rheostat is placed in series with the lamp to assure its operation in the desired range. These lamps are demountable and are selected according to the quantity of current required to represent the withdrawal from the pipeline network.

The lamps are placed in the load panel section of the analyzer and are connected to the circuits representing the pipeline network by electrical jumpers to permanently wired jacks connected to intersections of those circuits.

The source of power required to operate the analyzer can be any source of steady direct voltage such as a battery or a motor-generator set. By means of manually adjusted rheostats the desired differences of source voltages can be maintained to correspond with the known differences of head between any pair of sources, or between a single source and any other known point in the system.

Preparation for and Use of the Analyzer

The consulting engineering firm with which I am associated has used the McIlroy Analyzer located at Cornell University to analyze several water pipeline networks.

These distribution systems were not unusually large as to the number of major pipelines; however, several sources of supply at different heads were involved which added considerably to the complexity of the analyses. In all instances the field and office procedure prior to the use of the analyzer was practically identical and was as follows:

1. All of the necessary data was obtained from records for the particular water distribution system under study. This data included the size, length, age, and type of all mains in the distribution network. Field tests were conducted to determine representative "C" values of the water mains. From this basic data a head loss coefficient for each main in the network was computed which reflected the pipeline length, its size, type, and the relative roughness of the pipe interior. The ground elevations at all hydrants with reference to points of supply and storage were also obtained so that pressures throughout the system could be readily determined.

2. The water requirements and their distribution throughout the system were determined using meter and pumping records, and records of the variations of elevation in all storage facilities. From these records the maximum, the average, and the minimum water demands of the system were determined. In addition to the domestic and industrial demands for water, the quantities and location of water requirements for fire-fighting purposes were obtained from the New England Fire Rating Association. Studies were also conducted to estimate future water supply requirements of the system together with the estimated distribution of these future requirements throughout the existing network and at possible future additions to the network.

3. Due to the impracticability of determining the flow and pressure in each and every main within the distribution system, a trunk main system was established which comprised the larger sized mains of the system together with those smaller sized mains which formed loops with the trunk main system and those known to carry large flows.

Skeletonizing a system undoubtedly leads to inaccurate results as to the actual conditions, however, by careful reduction of the mains to equivalent mains and by a judical location of water demands on the network these inaccuracies can be held to a magnitude where they will not affect the final conclusions to be made from the analyses.

However, the McIlroy analyzer is so conceived that if it were practical and economically justifiable to do so, one could be constructed which would provide for almost an unlimited number of pipelines, sources, and loads.

At the several times when we utilized the Cornell Analyzer the capacity of this anlyzer was limited to approximately 90 pipelines 7 sources and 32 loads.

By way of comparison, the McIlroy Analyzer recently installed at Tufts University in Medford, Mass., has provisions for 710 pipelines, 225 electronically regulated loads, and 36 sources. Thus, the magnitude of the particular analyzer to be used as well as the practicability of the results to be obtained from the analyses is a factor that must be considered in skeletonizing the distribution network.

4. After all basic data regarding the physical and hydraulic characteristics of the system were determined, these fluid data were converted into electrical equivalents. Conversion to electrical equivalents involves the determination of three factors:

1. B factor, which is $\frac{V}{H}$ = volts per unit head loss.

2. G factor, which is $\frac{I}{Q}$ = amperes per unit flow rate.

3. O factor, which is the ration $\frac{k}{k_p}$, k = resistor coefficient and k_p = head-loss coefficient.

The selection of these factors depends upon the approximate total head loss and the range of flows expected in the system. The B factor is selected so that the average voltage per resistor is approximately 2.5 volts and the G factor is selected to give load currents suitable for the ratings of the ballast lamps which vary between .1 ampere and 1.0 ampere. The determination of the B and G factors establish the O factor for the resistor coefficients.

5. Following the conversion of the fluid quantities to electrical equivalents, an electric circuit diagram was prepared, using a standard form for the particular analyzer to be used. This diagram depicts the pipeline network with sources, load points and pipelines appropriately shown and numbered. For our first use of the analyzer this diagram was prepared by the technician operating the analyzer; however, for subsequent use these diagrams were prepared by our own personnel.

6. After the electrical data and circuit diagrams were completed, the next step was to set up the analyzer ready for use. This involved the insertion of the proper non-linear resistors in the panel circuits to represent the pipeline network, installation of constant-current lamps at the designated load points, and adjustment of the input current at the sources to the desired rates corresponding to actual pumping rates of the particular source or to any assumed rates of flow for purposes of study. Using the previously prepared electric circuit diagram, the operation of placing the distribution network on the electric analyzer was accomplished in a matter of only several hours time.

7. After the pipeline network and the demand loads were placed on the analyzer, the system was gradually energized. This was necessary to prevent the possible burning out of the highly loaded fluistors. The fluistors should not glow brighter than a cherry red color and any of those which were apt to glow brighter or burn out under full load were replaced by equivalent series or parallel combinations of fluistors. These combinations were mounted in separate banks of sockets and temporarily connected into the fluistor socket on the panel. All ballast lamps representing the loads on the system were also checked to ascertain that the correct currents were being drawn. Any variations indicated were corrected by adjustment of the manually operated rheostats at each load point.

Finally with the source voltage up to full load and all fluistors and ballast lamps operating properly, the analyzer was ready to use.

It is at this time that the direct-reading electric analyzer becomes a real asset to the Engineer. Up to this point, his work has consisted of compilation and programming of data and setting up the analyzer. The

Engineer may now measure and record the flow rate and head loss in each and every main in the network or he may only investigate certain portions of the network dependent upon the particular problem involved. A glance at the fluistors tells him where the trouble spots in the distribution system are located. The degree of brightness of the fluistors is indicative of the magnitude of the head loss in each section. However, those fluistors which were replaced by series or parallel equivalents may not necessarily glow brightly but the need for replacement is usually sufficient indication that a high head loss exists in that section.

To obtain the rate of flow in any pipeline of the network it is merely necessary to connect the panel mounted ammeter in series with the fluistor representing that pipeline and read the flow converted to gallons per minute. To obtain the head loss in that pipeline, the panel mounted voltmeter is connected in parallel with the fluistor representing that pipeline and the voltage drop or head loss in feet is read on the voltmeter. Special demountable scales are available for use on both the ammeter and voltmeter which allow flow readings to be made directly in gallons per minute and head loss read directly in feet.

These readings can be quickly taken as connections for the ammeter and voltmeter are made by inserting jumpers into built-in jacks, which are located at every pipeline intersection and for every pipeline. By noting the placement of the voltmeter leads, the direction of flow in each pipeline is determined.

In less than one hour's time, two persons can measure, read, and record the rate of flow and head loss for each section of a system approximating 90-100 pipes and 25 loops. A mathematical check on the analyzer can be made by adding the head losses around each loop and the flows in and out of each intersection. This can be done by the recorder simultaneously with the taking of the readings. When compared with the many hours required for trial and error computations of a network of this magnitude, the saving in time is considerable. Once the network is placed on the analyzer little time is required for the actual measuring, reading and recording of the data. Changes in the existing network such as the addition of new mains to form loops or to reinforce the existing mains, or perhaps a new source point or increased load points can be made very quickly and the resulting flows and head losses measured. Because this analyzer can be rapidly adjusted to reflect the results of possible changes in the distribution system, it is invaluable to the Engineer in that, for relatively little work, and in a very short time much information can be obtained concerning any proposed change in the network.

The performance records for the analyzer indicate that an overall error of less than 3% of the total head loss is obtained which is within satisfactory engineering accuracy for distribution network analysis. This error is on the conservative side and tends to show a slightly larger loss than would be obtained by using the Hazen and Williams formula. The accuracy of the results obtained from the analyzer is of course consistent with the accuracy of the input data relative to the distribution system.

In closing, I would like to thank Dorothy W. McIlroy, widow of the late Dr. McIlroy for her invaluable assistance rendered to representatives of our firm during the programming and operation phases of our work on the analyzer at Cornell University.

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